Gérard Albert Mourou
Doctor Honoris Causa

Laudatio Domini

Gérard Albert Mourou

Este o mare onoare să prezentăm acest laudatio pentru Profesorul **Gérard Albert MOUROU** la acordarea titlului de Doctor Honoris Causa al Universităţii din Bucureşti**.**

Domnul Profesor Gérard Albert MOUROU s-a născut în Albertville, Savoia, Franţa, în anul 1944. Este licenţiat în Fizică al Universităţii din Grenoble, Franţa din anul 1967. În anul 1970 a primit diploma pentru absolvirea celui de al treilea ciclu de studii de la Universitatea din Orsay. A susţinut Teza de Stat în Fizică la Universitatea Paris VII (Denis Diderot).

În prezent, Profesorul **Gérard Albert MOUROU** este una dintre cele mai proeminente şi remarcabile personalităţi ale Fizicii contemporane, activitatea sa având un impact substanţial în dezvoltarea Fizicii laserilor şi a Opticii moderne.

Din anul 1970, pentru trei ani, a fost colaborator ştiinţific al Universităţii din Laval, Quebec, Canada. După un an de studii postdoctorale la Universitatea San Diego, California, SUA, Profesorul **Gérard Albert MOUROU** a devenit Cercetător ştiinţific la École Polytechnique.

Din anul 1979, cercetările **Profesorului Gérard Albert MOUROU** au continuat în Grupul de Cercetări în domeniul picosecundelor din Laboratorul de Energetică bazată pe Laseri al Universităţii din Rochester, Rochester, New York, SUA, fiind conducător de grup. Între anii 1981 şi 1988 a fost Cercetător Ştiinţific cu grad maxim la acelaşi laborator. De asemenea, între anii 1983 şi 1987, a fost Profesor asociat la Institutul de Optică al Universităţii din Rochester. În anul 1988 a devenit Profesor la acelaşi institut. A fost „A.D. Moore Distinguished University Professor” la Departamentul de Inginerie electrică (Electrotehnică) şi Ştiinţa calculatoarelor la Colegiul (Facultatea) de Inginerie a Universităţii din Michigan.

Profesorul Gérard Albert MOUROU a fost Director de divizie la Divizia de Ştiinţe ultrarapide (Ultrafast Science Division) a Laboratorului de Energetică bazată pe Laseri al Universităţii din Rochester, între anii 1986 - 1988. În anul 1991 a devenit Director al Centrului de Ştiinţă Optică Ultrarapidă (Ultrafast Optical Science), din cadrul Fundaţiei Naţionale pentru Ştiinţă (National Science Foundation) şi al Centrului pentru Ştiinţă şi Tehnologie (Science and Technology Center), de pe lângă Universitatea din Michigan. Începând cu anul 2005, Profesorul **Gérard Albert MOUROU** este Director al Laboratorului de Optică Aplicată al Şcolii Naţionale Superioare de Tehnică Avansată (École Nationale Supérieure de Technique Avancée) şi Profesor la Şcoala Politehnică (École Polytechnique). Din anul 2009 este Profesor membru al Înaltului Colegiu al Şcolii Politehnice (Haut Collège de l’École Polytechnique).

Contribuţiile de excepţie ale Profesorului **Gérard Albert MOUROU** sunt în domeniul laserilor ultrarapizi, în special, în domeniul dezvoltării laserilor de mare putere cu pulsuri de durată scurtă şi foarte scurtă, precum şi în Optica neliniară relativistă. Aceste contribuţii au la bază tehnica cunoscută sub numele de

„amplificarea modulară a pulsurilor” (*Chirped Pulse Amplification*), inventată în perioada în care a lucrat la Universitatea din Rochester, în colaborare cu Dana Strickland. Printre realizările remarcabile se numără crearea de câmpuri de intensitate ultraînaltă şi generarea de radiaţie de THz. Această tehnică face posibilă atât obţinerea de maxime mari de putere, cât şi miniaturizarea sistemelor laser.

În domeniul aplicaţiilor, trebuie menţionată activitatea de pionerat în domeniul Oftalmologiei de femtosecunde, activitate desfăşurată alături de colegi din domeniul Medicinii la Universitatea din Michigan. Laserul de femtosecunde este folosit acum pentru realizarea de tăieri foarte precise în transplantul de cornee sau în corectarea miopiei. De aceste tratamente au beneficiat milioane de pacienţi.

Activitatea ştiinţifică a **Profesorului Gérard Albert MOUROU** este reflectată de articolele publicate în cele mai prestigioase reviste de fizică, cum ar fi: *Review of Modern Physics* şi *Physical Review Letters*, unele dintre ele fiind cele mai citate lucrări apărute în ultimele decenii în reviste științifice de prestigiu. Numai în ultimii douăzeci de ani, **Profesorul Gérard Albert MOUROU** a publicat peste **300 de articole** în reviste cotate în sistemul ISI. Acestea au fost citate de peste **11.000 citări**, ceea ce face ca **factorul Hirsh** al domniei sale să fie **53.**

Profesorul Gérard Albert MOUROU a fost în întreaga sa carieră ştiinţifică un participant activ la rezolvarea problemelor comunităţii ştiinţifice, de aceea, domnia sa a fost ales să facă parte din diferite asociaţii profesionale internaţionale ale fizicienilor. Astfel, a fost ales membru în Comitetul de avizare al Laboratorului de Utilizare a Laserilor de Mare Intensitate, de la Şcoala Politehnică

(École Polytechnique, Franţa), membru în Comitetul de avizare al Directoratului pentru Ştiinţe Fizice şi Matematice al Fundaţiei Naţionale de Ştiinţă (National Science Foundation, SUA), membru al Comitetului de avizare pentru Fizică nucleară/Fizica energiilor înalte al Fundaţiei Naţionale de Ştiinţă (National Science Foundation), SUA, membru al Centrului de Excelenţă al Fundaţiei Naţionale pentru Ştiinţă, membru al Comitetului de avizare al Centrului de Optică teoretică, membru al Biroului editorial al revistei *Laser Focus*, membru al Biroului editorial al revistei *Applied Physics B* etc.

Este membru al Academiei Naţionale de Inginerie a SUA, membru străin al Academiei de Ştiinţe a Rusiei, membru străin al Academiei de Ştiinţe a Austriei, membru străin al Academiei Lombarde de Ştiinţe şi Arte (Italia). Ca o recunoaştere a contribuţiilor de excepţie ale domniei sale, Profesorul **Gérard Albert MOUROU** a primit numeroase premii şi distincţii. Astfel, Academia Chineză de Ştiinţe i-a acordat Premiul „Catedra Einstein” în 2010, iar Societatea de Optică a Americii i-a conferit Premiul „Charles H. Townes”, în anul 2009. De asemenea, Academia Naţională Franceză a acordat Profesorului **Gérard Albert MOUROU**, în anul 2007, Marele Premiu Carnot. Printre premiile obţinute se numără: Premiul Edgerton – din partea SPIE, Premiul Sarnoff din partea IEEE şi Distincţia pe anul 2004 a IEEE/LEOS pentru Electronică cuantică. Este membru al Societăţii de Optică din America (Optical Society of America) şi membru al Institutului de Inginerie Electrică şi Electronică (Institute of Electrical and Electronics Engineers).

Profesorul **Gérard Albert MOUROU** a propus Forumului European de Strategie în domeniul Infrastructurilor de Cercetare, alături de alţi doisprezece parteneri europeni, o nouă infrastructură numită **„Infrastructură pentru Lumina Extremă" [Extreme Light Infrastructure (ELI)].** Începând cu anul 2007, România este membru activ al unui sub-program al acestui proiect, şi anume: **Extreme Light Infrastructure-Nuclear Physics (ELI-NP).** Pe platforma de Fizică de la Măgurele se va construi acest al treilea pilon al acestui tip de infrastructură, în cadrul Programului Cadru 7 al Uniunii Europene. În efortul de a integra comunitatea românească de Fizică în acest proiect, Profesorul **Gérard Albert MOUROU** a organizat mai multe întâlniri, la diferite niveluri, cu participarea unor membri ai Parlamentului României şi Ministerului Educaţiei, Cercetării, Tineretului şi Sportului, dar şi numeroase manifestări ştiinţifice cu subiecte din acest domeniu, toate desfăşurate în România. Aceste eforturi au permis organizarea **primei conferinţe internaţionale în domeniul infrastructurilor pentru lumina extremă, numită „Lumina la Intensităţi Extreme" ("Light at Extreme Intensities")**, în anul 2009, la Braşov. Datorită acestor eforturi, în acelaşi an, 2009, România a fost desemnată să construiască pilonul de Fizică nucleară al Infrastructurii pentru Lumina Extremă. Este important de menţionat şi implicarea domniei sale în stabilirea unor conexiuni puternice cu comunitatea ştiinţifică românească de Fizică. Un exemplu în aceste sens este organizarea, cu sprijinul domniei sale a Conferinţei Internaţionale de Laseri Ultraintenşi (**International Conference of Ultraintense Lasers)**, la Mamaia, în vara anului 2012.

Întreaga activitate ştiinţifică şi administrativă în slujba Ştiinţei a domnului **Profesor Gérard Albert MOUROU** este caracterizată de o mare şi profundă creativitate, intuiţie ştiinţifică, focalizate atât pe concepte fundamentale, cât şi pe aplicaţii. **Contribuţia domniei sale la dezvoltarea Fizicii laserilor şi Opticii neliniare este legată de combinaţia unică dintre abilităţile experimentale excepţionale, înţelegerea profundă a conceptelor teortice şi o intuiţie remarcabilă.**

Acordarea titlului de **Doctor Honoris Causa al Universităţii din Bucureşti,** domnului **Profesor Gérard Albert MOUROU** reprezintă o **recunoaştere simbolică a marilor sale merite ştiinţifice** şi un **nou pas înainte** în **întărirea colaborărilor ştiinţifice şi educaţionale dintre Universitatea din Bucureşti şi universităţile franceze, dintre oamenii de ştiinţă din România şi din Franţa.** Am convingerea că, prin celebrarea domniei sale astăzi, la Universitatea din Bucureşti, este semnificativă nu numai pentru membrii corpului academic al Universităţii noastre, dar şi pentru întreaga comunitate ştiinţifică din ţara noastră.

Decan,
Prof. univ. dr. Alexandru JIPA

Laudatio Domini

Gérard Albert Mourou

It is a great honour to deliver this laudatio for the laureate of Doctor Honoris Causa of the University of Bucharest title to Professor **Gérard Albert MOUROU.**

Gérard Albert MOUROU was born in Albertville, Savoie, France, in 1944. He received his B.S. in Physics from Université de Grenoble, France (1967) and the PhD from Université d'Orsay (1970). In 1973, he sustained Thèse d'État in Physique at Université Paris VII.

Professor **Gérard Albert MOUROU** is one of the most prominent and remarkable personalities of the contemporary Physics, his activities having a substantial impact in the development of the Laser Physics and modern Optics.

From 1970, for three years, he was Scientific Cooperant at Université Laval, Quebec, Canada. After a one year Postdoctoral Fellowship at San Diego State University, California, he became Scientist at École Polytechnique.

Since 1979, the researches of **Professor Gérard Albert MOUROU** were continued as Group Leader of Picosecond Research Group at the Laboratory for Laser Energetics, University of Rochester, Rochester, New-York. He activated as Senior Scientist at the Laboratory for Laser Energetics between 1981 and

1988, as Associate Professor between 1983 and 1987, and then as Professor at Institute of Optics, University of Rochester. He was until recently the A.D. Moore Distinguished University Professor at the Department of Electrical Engineering and Computer Sciences, College of Engineering, University of Michigan.

He was in charge as Division Director at Ultrafast Science Division, Laboratory for Laser Energetics, Rochester from July 1986 until 1988. In 1991 he became the Director of the Center for Ultrafast Optical Science, a National Science Foundation and Technology Center located at the University of Michigan. Since 2005 Professor **Gérard Albert** MOUROU is the Director of the Laboratory of applied Optics at École Nationale Superieure de Technique Avancée and Professor at the École Polytechnique. From 2009 is Professeur Membre du Haut Collège de l'École Polytechnique.

The outstanding contributions of Professor **Gérard Albert MOUROU** are in the field of ultrafast lasers, especially to the development of short-pulse high-power lasers and advances in relativistic nonlinear Optics. This progress was possible due to the laser amplification technique known as "Chirped Pulse Amplification" invented by him at the University of Rochester in collaboration with Dana Strickland. Important accomplishments include the creation of ultrahigh-intensity fields, generation of terahertz radiation. This technique makes possible not only a higher peak power, but also leads to miniaturized laser systems.

In the area of the applications, it should be mentioned that he pioneered the field of femtosecond ophthalmology together with medical colleagues at University of Michigan, too. The femtosecond laser is employed now to perform very precise cut for corneal transplant or myopia correction and millions of patients received such procedure.

The scientific activity of **Professor Gérard Albert MOUROU** is reflected by essential publications in the most prestigious physics journals, including *Review of Modern Physics* or *Physical Review Letters*. Some of his most cited papers appeared in the famous journal *Science*. Only in the last twenty years, **Professor Gérard Albert MOUROU** published over **300 papers** in ISI quoted journals which received more than **11.000 citations and a Hirsh Index 53.**

Professor Gérard Albert MOUROU was in his entire scientific career an active participant in the solving of problems of the scientific community. Therefore, he was elected in different international associations of the physicists. He was Advisory Board Member of the Laboratory for the Usage of Intense Lasers (École Polytechnique, France), Advisory Board Member for the Mathematical and Physical Sciences Directorate of the National Science Foundation, Advisory Board Member for the NSF Nuclear/High Energy Physics, National Science Foundation Center of Excellence, Advisory Board Member for the Center of Theoretical Optics, Member of Editorial Board of Laser Focus, Member of the Board of Editors for Applied Physics B.

He is a member of US National Academy of Engineering, Foreign Member of Russian Academy of Science, Foreign Member of Austrian Academy of Science, Foreign Member of Lombardy Academy of Science and Letters, Italy.

As recognition of his outstanding contributions, he has received many awards. He has been the recipient of the Einstein Chair 2010 from the Chinese Academy of Science, the 2009 Charles H. Townes Award from the Optical Society of America, the 2007 Grand Prix Carnot from the French National Academy, the Edgerton Prize from SPIE, the Sarnoff Prize from the IEEE and the 2004 IEEE/LEOS Quantum Electronics Award. He is a fellow of the Optical Society of America and a fellow of the Institute of Electrical and Electronics Engineers.

Professor **Gérard Albert MOUROU** proposed to the European Strategy Forum on Research Infrastructures, together with twelve European partners, a new facility called **Extreme Light Infrastructure (ELI).** Since 2007, Romania is an active member in this project, **Extreme Light Infrastructure-Nuclear Physics (ELI-NP)** at Măgurele being one of the three pillars of the infrastructure facility, within the Frame Programme 7 of the European Union. In the effort to unify the Romanian Physics community in this project, Professor Gérard Albert MOUROU organized many meetings, at different levels, including Romanian representatives of the Parliament and Ministry, and scientific academic representatives. These efforts permitted the organisation of the **first international conference on ELI**, namely **"Light at Extreme Intensities"**, in 2009, at Braşov. Due these efforts, in 2009, too, Romania received the Nuclear Physics pillar of the Extreme Light Infrastructure. It is important to mention here, too, that his involvement in the establishing strong connections with the Romanian Physics community will be fructified by the organization of the **International Conference of Ultraintense Lasers**, this year, at Mamaia.

The entire scientific and administrative activity of **Professor Gérard Albert MOUROU** is characterized by a great and profound creativity, scientific intuition, focused both on fundamental concepts and applications. **His contribution to the development of the Laser Physics and nonlinear Optics is related to the unique combination of outstanding experimental skills, clear theoretical understanding and remarkable intuition.**

The awarding of the title of **Doctor Honoris Causa of the University of Bucharest** to **Professor Gérard Albert MOUROU** represents a **symbolic recognition of his great scientific merits** and a **new step** forward in the **strengthening of the scientific and teaching collaborations between the University of Bucharest and the French Universities, among the scientists from Romania and France.** I am convinced that today's celebration is significant not only for the members of the academic body of our University, but also for the entire scientific community of our country.

Dean,
Prof. univ. dr. Alexandru JIPA

Curriculum Vitae

Gérard Albert Mourou

Gérard Mourou is Professor at the École Polytechnique and Director of the Institut de Lumière Extrême. He is also the A.D. Moore Distinguished University Emeritus Professor of the University of Michigan. He has been one of the most creative and productive scientists in the field of ultrafast and ultrahigh field science. He is often regarded as the “father” of the high intensity and ultra high intensity field.

His contribution touches most of the fields of science and technology extending from high-speed electronics with the invention of the THz electro optic sampling to medicine where he started the field of femtosecond ophthalmology and now Relatistic and Ultrarelativistic Optical Science.

His most important contribution is certainly the invention at the University of Rochester with his student Donna Strickland of the laser amplification technique universally used today and known as Chirped Pulse Amplification (CPA).

The concept was demonstrated in 1985 and will revolutionize laser-matter interaction making possible new applications in ophthalmology and by moving the field into the relativistic regime. The peak power at that time was GW. In 1988, he showed that TW power could be produced on the Table Top. The system was dubbed, T^3 for Table Top Terawatt laser. Realizing that PW could be generated with existing larger laser, built already for laser fusion-, in 1987, he wrote a paper on "En Route vers le Petawatt". He described how PW could be produced. Using Mourou's suggestion, the first Petawatt was demonstrated 10 years later, in 1996 by M. Perry at LLNL. **The possibility to produce PW pulses made a new concept called fast ignition possible. Today Fast ignition is the major topic in laser fusion. It gave a new wind to this field.**

In 1988, he moved to the University of Michigan and in collaboration with the French CEA, he demonstrated that the CPA concept could be integrated to the new Nd: glass laser fusion system (laser P102) to produce the enormous power at the time of 50TW. **This experiment on P102 is considered to have opened up the field of ultrahigh intensity science.**

He was the first to perform experiments with CPA. He teamed up with the group from Montreal. Numerous experiments on laser matter interaction in the relativistic regime were done in collaboration with the group of H. Pepin, J.C. Kieffer from INRS, Montreal.

At the University of Michigan, he showed that CPA laser could work with Ti sapphire laser at **very high repetition rates (kHz). They built the first kHz system** that was widely duplicated and sold by the major laser companies, Spectra Physics, Coherent, but also by Clarke-MXR, Thalès, Amplitude, etc. Today, there are few thousands of these systems in the world laboratories and companies.

In 1993, as they tried to propagate TW pulses in air, the Michigan team **discovered the phenomenon of self-channeling in**

air. They explained the phenomenon with a model that is still used today. They made the first detailed study on filament size, energy, particle density, etc.

In 1993, CPA offered a very simple way to measure and study the damage threshold of materials as function of pulse duration. They discovered the **anomalous behavior in dielectrics of the damage threshold versus pulse duration and its deterministic behavior in the femtosecond regime.** This effect is at the heart of micromachining, nanomorphing, eye surgery, etc.

In 1993, they applied the precise ablation behavior of the femtosecond pulses to ophthalmology. **This was the beginning of femtosecond ophthalmology**. They started a company Intrase and demonstrated a procedure that has been used today on 2 millions patients, for vision correction.

In 1991, at the University of Michigan, he **founded the Center for Ultrafast Optical Science.** One of the CUOS major research axes was laser matter interaction in the relativistic regime. With colleagues at CUOS, he made some pioneering works in:

a) relativistic non linear optics, with the demonstration of relativistic self-focusing,

b) laser plasma acceleration of electrons,

c) laser plasma acceleration of ions,

d) nuclear reaction produced by laser-produced ions,

e) X-ray generation.

He also introduced the concept of relativistic pulse compression in the lambda cubed regime that could be the way in the future to produce attosecond pulses with high efficiency from relativistically moving plasma mirror.

Looking to the future. With colleague T. Tajima, he explored ideas to produce even higher peak power, i.e. in the exawatt and zettawatt regime. This peak power, if focused on a diffraction limited spot size, could produce 10^{26}-10^{28}W/cm2 (see vision paper in the list of key publications) to approach the Schwinger field.

When I came back to France from the USA, 4 years ago, I tried to reduce to practice this vision by proposing to build an exawatt infrastructure with 12 European countries. This infrastructure is called ELI (Extreme Light Infrastructure). It will make possible to go into the ultra relativistic regime and also to explore Nonlinear QED to test the vacuum structure and general relativity.

The impact of CPA:
A Revolution in Laser Matter Interaction

The field of High field laser physics continues to expend at an explosive pace. The number of papers published and scientists involved in this field is estimated at several thousands. The field scientific activity can also be estimated by the numerous workshops, and conferences on ultrahigh intensity.

This field is one of the major fields in physics in Europe, in Asia and in the US. Because of its relatively low cost many countries even with limited scientific budget have or are planning to construct high intensity facilities. There are more than 1000, mJ, kHz lasers in the world. With such a multiplicity of lasers, important results have been demonstrated that extend from the eV to the sub-GeV regime.

The scientific impact of CPA has been considerable. It has penetrated a large number of scientific disciplines and has extended the field of laser optics from the meV(THz) to the GeV to include atomic physics and molecular physics, biology, neutron science, nuclear physics, thermonuclear fusion, astrophysics, nuclear physics, high energy physics, general relativity, nonlinear QED and cosmology.

By making possible an increase of laser peak power by 10^6, an average power of 10^3, Chirped pulse Amplification, revolutionized the field of laser-matter interaction. It gave access to new regimes of interaction that were not thought possible. The hallmark of these interactions has been micromachining, ophthalmology, harmonic generation, the generation of high-energy particle and radiation beams. Also the nonlinearities involved with the interaction causes extensive broadening of the laser spectrum that offers the possibility to compress the incident laser pulse from femtosecond to the attosecond regime and in the future from attosecond to zeptosecond.

In this chapter, we are making an attempt to describe the numerous applications in the different intensity regimes. As intensity metric we will use the relativistic intensity I_R. This intensity corresponds to the one where the electron driven by the laser field, becomes relativistic over the period of light. For 1mm light it is equal to ~10^{18}W/cm2. We usually distinguish three interaction regimes: the sub-relativistic regime, the relativistic regime and more recently the ultra-relativistic regime.

1. Sub-relativistic intensity regime

In the sub-relativistic regime I<10^18W/cm2, we distinguish interaction with gases and solids.

This regime was in principle accessible prior to CPA, except that CPA made it more compact, cheaper, with much higher average power due to an increase of 1000 times in repetition rate. kHz, mJ system became the workhorse of this regime.

1.1. Interaction with Gases

1.1.1. Attosecond physics. CPA systems, coupled with short pulse compression in gas filled capillaries and harmonic generation has been one of the key elements in the generation of sub-femtosecond pulses, (G. Sansome et al. Science 314, 4432006).

1.1.2. Atmospheric science. The channeling of intense lasers as first discovered by Mourou and his group is used as new tool with system like the Teramobile to probe molecular atmospheric species. A. Braun, G. Korn, X. Liu, D. Du, J. Squier, and G. Mourou, "Self-Channeling of High-Peak-Power Femtosecond Laser Pulses in Air", *Opt. Lett.* 20, 73-75 (January 1, 1995).

1.2. In solids

1.2.1. Femtosecond ophthalmology. It represents the most important societal application of femtosecond laser. The salient property of laser breakdown that was for the first time demonstrated by Mourou and its group, is its deterministic character, deprived of collateral. With his coworkers, he started the field of femtosecond ophthalmology, that is used today for vision correction. The company that has been created, “Intralase” (subsequently sold to AMO) has treated as many as 5 million patients. They are extending the applications of femtosecond ophthalmology to other pathologies like glaucoma, where small holes are performed in the sclera to relieve the undesired over pressure. The same technique is used for corneal transplant. In corneal transplant the enormous advantage over the mechanical trephine is that a only part of the cornea in thickness can be removed and replaced.

- Juhasz T, Loesel C, Horvath C, Kurtz R M, Mourou G, “Corneal refractive surgery with femtosecond lasers”, *IEEE Journal of Quantum Electronics*, 1999, 5, 902 - 09.
- Z. Sacks, D. L. Craig, R. M. Kurtz, T. Juhasz, G. Mourou, “Spatially resolved transmission of highly focused beams through cornea and sclera between 1400 and 1800 nm”, *SPIE Proceedings,* 1999.
- Z. S. Sacks, F. Loesel, C. Durfee, R. M. Kurtz, T. Juhasz, G. Mourou, “Transscleral photodisruption for the treatment of glaucoma”, *SPIE Proceedings 1999*.

1.2.2. Nanomorphing and applications to biophysics and nanofluidics

With colleague A. Hunt, Mourou used the deterministic property of the interaction to make nanometer size features for applications in analysis, nanofluidics.

Ajit P. Joglekar, Hsiao-hua Liu, Edgar Meyhöfer, Gerard Mourou, and Alan J. Hunt, “Optics at critical intensity: Applications to nanomorphing”, PNAS 2004 101: 5856 - 5861

1.3. High quality X-Ray laser

Femtosecond Table top Soft x ray has been demonstrated by using laser plasma amplifier seeded by high harmonics from gases. This source exhibits high energy, highcoherence and full polarization. P. Zeitoun et al Nature 431, 426 (September 2004)

2. Relativistic Intensity Regime

In this regime the laser intensity is above I_R. The highest laser intensity is 10^{22}W/cm^2 that has been obtained by Mourou's group, that is 10^4 times $I_{R,}$ see Bahk et al. **For a general overview of the interaction in the relativistic regime see G. Mourou, T. Tajima and S. Bulanov, "Optics in the Relativistic Regime"** ***Review of Modern Physics*** **78. Jan - Mar 2006.**

- N. Naumova, I. Sokolov, J. Nees, A. Maksimchuk, V. Yanovsky, and G. Mourou, "Attosecond Electron Bunches", *Phys. Rev. Lett.* **93**, 195003 (2004).
- S. W. Bahk, P. Rousseau, T. A. Planchon, V. Chvykov, G. Kalintchenko, A. Maksimchuk, G. A. Mourou, and V. Yanovsky, "Generations and characterization of the highest laser intensities (10^22 W/cm^2)", *Opt. Lett*. Vol. **29**, No. 24, p 2837, Dec 15, 2004.
- N. M. Naumova, J. A. Nees, B. Hou, G. A. Mourou, and I. V. Sokolov, Isolated attosecond pulses generated by relativistic effects in a wavelength-cubed focal volume, *Opt. Lett.* **29**, 778 (2004).
- N. M. Naumova, J. A. Nees, I. V. Sokolov, B. Hou, and G. A. Mourou, "Relativistic generation of isolated attosecond pulses in a l^3 focal volume", *Phys. Rev. Lett*. **92**, 063902 - 1 (2004).

2.1. Interaction with Gases

2.1.1. GeV Electron accelerations, Quasi monoenergetic beams, Precise all optical injection technique

The electron acceleration continues to be the most important application. Laser acceleration over 3cm to the GeV with a few percent energy spread regime has been demonstrated by W. Leeman et al. (2006). An all-optical new injection technique has been demonstrated leading to adjustable electron energy of 2% (J. Faure et al., 2006).

- W. P. Leemans et al., *Nature Physics 2*(10), 696 (2006).
- J. Faure, C. Rechatin, A. Norlin et al., *Nature 444*, 737 - 739 (2006).

2.1.2. Betatron oscillation. In the relativistic regime, the electrons accelerated to high energy can produce keV high-energy radiation by betatron oscillation, as demonstrated by A. Rousse, K. Ta Phuoc, R. Shah, A. Pukhov, E. Lefebvre, V. Malka, S. Kiselev, F. Burgy, J.P. Rousseau, D. Umstadter, and D. Hulin, *Phys. Rev. Lett.*, **93**, 13 135005 (2004).

2.2 Interaction with solids

2.2.1. Proton acceleration

The electrons being accelerated will drag behind protons and ions. This effect has been first observed by the group of M. Perry at LLNL (E. L. Clark et al 2000). This topic has been extremely active. Ions have been produced from 1 to 100MeV. An abundant literature has been produced. Few hundred papers have been written on laser-produced protons. Note the importance of ion generation for proton therapy.

- E. L. Clark *et al.* 2000 “Energetic heavy ion and proton generation from ultra-intense laser-plasma interaction with solids", *Phys. Rev. Lett.* **85** 1654.

2.2.2. Fast ignition

Fast ignition is the most important topics in inertial confinement fusion. The concept of fast ignition was demonstrated by ILE Osaka and Rutherford (R. Kodama et al. 2000) using a special target with a cone arrangement. In this concept, one decouples the compression phase from the ignition one. Instead of relying on self-ignition of the D-T fuel, akin to the spark-plug engine, a very short and intense pulse produced by a CPA system heats up the fuel locally to drive the ignition. Few alternatives are explored for the short pulse: the laser itself, short pulse of electrons and short pulses of ions. This concept will lower the ignition threshold by a large factor. It could make possible one day, fusion a reality.

Most of the large laser fusion programs are adding to their large-scale systems a CPA petawatt system for fast ignition. This is true for Rochester that has built OMEGA EP, ILE in Japan building FIREX, France building PETAL and NIF.

- R. Kodama, et. al., "Nature", 418(2002) 933, *Nature* **431**, 426 - 429 (23 September 2004).

2.2.3. Harmonic generation and attosecond pulses

In the relativistic regime, the interaction laser-solid is responsible for high harmonic generation. This relativistic effect is due to the relativistic motion of the critical surface. It was predicted by Bulanov 15 years ago. It has the property to be deprived of cut off. Relativistic harmonics has been observed up to the 25 orders, F.Quéré et al., *Phys. Rev. Lett*. **96**, 125004 (2006).

Using Vulcan extremely high harmonics up to few thousand were observed by B. Dromey, M. Zepf et. al. *Phys. Rev. Lett.* **99**, 085001 (2007).

2.2.4. Nuclear Physics

The laser electric field, even in the relativistic regime is too feeble compared to the nuclear electric field to produce any reaction. However, the "g" radiation produced and the particles in the MeV regime can. A very large body of work has been performed. We can only cite some of the salient ones:

- Photo fission by K. Ledingham et al. *Phys., Rev. Lett.* 84: 899, 2000.
- Photonuclear fission by T. Cowan et al., *Photonuclear fission Phys. Rev. Lett* 84.903, 2000.
- Fission of actinides by, H. Schwoerer et al., *Europhys. Lett.* 61:47, 2003.
- Proton and ion reaction by, R. Snavely et al., *Phys. Rev. Lett.* 84: 675, 2004.
- Transmutation of of iodine 129, J. Magill et al., *Appli. Phys. B*, 77: 77:387, 2003.
- Transmutation of nuclear waste by K. Ledingham et al., *J. Phys. D: Appl. Phys.* 36, L79 (2003).

3. The Ultra Relativistic regime, I> 10 24W/cm2: The extreme Light Intensity régime

Until now, the laser intensity 10^{18}-10^{22}W/cm^2 could only drive the electrons in the relativistic regime. The ions are too massive to move relativistically. If in a plasma we want to drive the ions relativistically, because of the masse of the proton 2000 times higher than electron, we need to increase the intensity by 6 orders of magnitude or 10^24 W/cm2, if we want to move the proton and all the other ions for that matter relativistically. We called this regime the ultrarelativistic regime. In this regime, photons, electrons and ions move at the velocity of light.

The interaction is expected to produce higher quality X-ray, g-ray, and particle beams.

These very high intensities need a very powerful laser in the exawatt range 10^18W. Because of the large size and cost of such a laser, only a consortium of countries will be able to afford it. So the infrastructure ELI is a EU infrastructure on the ESFRI roadmap.

ELI: A New Paradigm for High Energy Physics

The recently proposed infrastructure ELI (Extreme Light Infrastructure) by thirteen European Union countries will be the first facility capable of studying fundamental laser-matter interaction in the new regime of ultra-relativistic optics reaching into the fundamental QED and possibly QCD regimes. ELI facility will be capable of creating electric fields in a “macroscopic” space domain to short-circuit the vacuum, the best insulator.

The peak power of ELI in the exawatt regime, that is 100000 times the world grid power over a brief instant will be able to produce, synchronized, high energy radiation and particle beams with extremely short time structure in the attosecond and zeptosecond time domain. These unique characteristics unattainable by any other means, could be combined to offer a new paradigm to the exploration of the structure of vacuum to respond to one of the most fundamental questions: how can light propagate in vacuum, how can vacuum define the speed of light and how can it defines the mass of all elementary particles. The ELI unique features: high field strength, high energy radiation and particle beam, their ultra-short time structure and impeccable synchronization, herald the laser entry in High Energy Physics that could stimulate the interest in the physics of the vacuum state in presence of strong external fields.

Towards exawatt laser power and sub-attosecond pulses Interview with Gérard Mourou, project coordinator of the Extreme Light Infrastructure (ELI)

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What physics could evolve if we neglected all the current technical problems in laser physics? Gérard Mourou and some colleagues started to explore this question more than ten years ago.

The result was a broad vision of new laser physics in the ultra high intensity regime. Now the idea has gained momentum with a giant European research collaboration. Andreas Thoss spoke to Gérard Mourou about the initiative‘s current status.

Optik & Photonik: Professor Mourou, after 28 years in some of America‘s top Universities, you returned to France. What was the reason?

Gérard A. Mourou: The reason was very simple. When I left in 1978 with my wife, I had already spent some years in America. I got a very generous offer from the University of Rochester. When I left, it was only supposed to be for a few years. But those few years, you know, became 28 years. And then I reached an age where you think about going back home. I had to fulfill my promise to my wife, so we came back.

O&P: But you didn‘t return just to retire?

G.M.: That‘s right.

O&P: You have started quite a number of research projects in your life. But ELI (the Extreme Light Infrastructure) stands out, even in this impressive list. Could you briefly describe what ELI is?

G.M.: ELI aspires to be the most intense laser in the world. By most intense, I don’t mean the biggest. If you look at NIF at Livermore, or Mégajoule in Bordeaux, you know that the size of the laser is a function of energy, not a function of power. ELI is a different type of laser, we really want power and intensity. Why do we want that? We are not building this just to have the biggest, most powerful laser. There is of course a scientific reason we may finally get a chance to do all the vacuum physics that we have dreamed of since the sixties. The interaction of light with a vacuum is very important. All the laws of physics and all the main physical constants are basically dictated by a vacuum.

O&P: If we may turn to the organization, how many institutes are now involved within ELI?

G.M.: Oh, it’s enormous. We have 13 countries, each with a number of labs. So, roughly speaking, there are about 50 institutes involved.

O&P: Aside from a number of existing sites, you have some plans to set up completely new sites. When and where?

G.M.: There are basically four sites. This is related to the project‘s four pillars. One pillar is electron acceleration. This will be at a site in Prague. A second pillar will be attosecond short pulses, intended for Szeged, Hungary. The third pillar is nuclear physics, to be located in Măgurele, România. The fourth pillar will be high intensity physics, the location for which will be decided in 2012. We are now in the preparatory phase. In three years, these projects will be operative. These projects are the first big scientific projects for the new European Union members from eastern Europe. There is a budget of 800 million Euros, with about 280 million Euros for each country.

O&P: What was the biggest challenge in this project?

G.M.: Well, it actually went smoothly. It was the right mix. The countries were looking for something. ELI became a number one project in these countries.
O&P: You already mentioned vacuum physics as a final goal of the new systems. What other ideas are behind ELI?
G.M.: One idea is to try to produce extremely short pulses. If we look at pulse duration as a function of the years, you will notice that all the progress came whenever we improved the pump laser power. So there is a strong correlation between power and pulse duration. If we look at free running, q-switched, mode locking, Kerr lens mode locking, pulse compression techniques, attosecond pulses, it was always necessary to increase the power in order to get shorter pulses. And that is one of the big targets of ELI – to produce highest peak power at highest intensity, and also to produce extremely short pulses. If we produce extremely short pulses, of course we produce extremely short wavelengths. Also very high intensity photons and high energy particles. This is what we can achieve with high laser power.
O&P: Tuning systems to ever higher power is one thing, but what real changes do you expect at those high intensities?
G.M.: Since 1990 after the invention of CPA, we have been in the regime of relativistic optics.
The interaction of light with electrons becomes different because we have to include the v x B term now, which really makes the law of optics different. In 1990, we showed that we could get intensities to 10^{18} W/cm^2 and more where the v x B is not negligible anymore as in classical optics or even in nonlinear optics. In fact, it becomes dominant, pushing the electron and enabling electron acceleration.

This is at 10^{18} W/cm². But there is another regime just after that. This one goes into the ultra relativistic regime at 10^{24} W/cm². At this point we start to accelerate ions. In the relativistic regime, we accelerate electrons to relativistic energies. In the ultra relativistic regime at six orders of magnitude more intensity, we have relativistic ions. This is very important because in this regime the electrons, the ions and the photons are all relativistic. So the interactions, the energy exchange between the pump laser, electrons and ions is kind of ideal. And if we go one step further, at 10^{29} W/ cm², we get pair generation. ELI is aiming for 10^{25} W/cm². So we are going to be well into the ultra relativistic regime, which is good, but we are not at the 10^{29} W/cm² level. Which is only partially true as we start to produce pairs long before that intensity. Also we can use some of the byproducts generated at 10^{25} W/cm² such as gamma rays, x-rays and high-energy electrons that we can mix with the laser to reach the ultimate level.

O&P: So I guess radiation is problematic.

G.M.: That's right. Of course radiation is a major concern. Handing over a lab to work in this regime is very much like being in the field of nuclear physics. This is what we have to be concerned about. And there is a historical point. The laser was invented in 1960. We just celebrated 50 years this year. CPA started in about 1990. Until then, lasers were basically used for atomic physics – the science of electron volts. Now, with ELI at 10^{24} W/cm², we can start with nuclear physics. And that is one of the major targets of ELI: to go into nuclear physics. Here it becomes clear why the combination of intensity plus short pulses is so beautiful. With ultra-short pulses, we can look at electrons dancing around the nucleus, just as Ferenc

Krausz did. If we have ultra-short pulses in the attosecond regime or even shorter, then we can look at very fast nuclear physics. Now with ELI large scale systems, we can open the door for such measurements.

O&P: If we look at the roots of ELI, you brought your nuclear physics experience, and even some particle physics experience, into the laser field, right?

G.M.: That's correct, absolutely. ELI really gives us the opportunity to explore things with lasers which were previously done with particle accelerators. Now we can do that with just lasers.

O&P: What makes ELI different to other European research projects such as XFEL or ITER? What is new about this idea?

G.M.: ELI is not just after one goal, such as ITER for instance. ITER is trying to generate energy, a really important project for our society. With ELI, the range of research is much more diversified. It is research in general but we go into new domains. We do this differently compared to conventional high energy physics. Usually, they are building a very expensive machine with one particular goal in mind, such as generating the Higgs boson, for instance. With ELI we are going to explore an entirely new domain. Since 1960, we have been researching the electronvolts domain, with very compact systems. With somewhat bigger systems, we have already done much research in the relativistic domain.

O&P: With hall size systems?

G.M.: In financial terms, I would say a few million Euros per system. Now in the new regime, we discover a lot of exciting stuff. We do it in the same way but with different lasers.

O&P: Can you tell me more about the top three or four research targets that you are focusing on at the moment?

G.M.: Yes, the first is our research on high energy particles. With electrons, we can certainly set up much more compact systems for electron acceleration. One target will be the demonstration of 100 GeV. 100 GeV is twice the performance of SLAC. We should also be able to produce relativistic ions, GeV ions. One application will be in proton therapy. Of course, we don't need GeV ions for that. But in order to study its generation and effects, it will be necessary to produce GeV ions. We want to know the whole story, to find out the best regimes for proton therapy, for material science etc. Then we have high-energy radiation. In a sense, we could try to do a compact XFEL. Instead of having a large km-size accelerator to produce 10 to 15 GeV electrons, we are going to produce it in a smaller setting. The electrons have to be of high quality, with a substantial amount of charges. Then we can do the same thing: we have the source and the magnets, and can produce X-rays or coherent X-rays. The next one is exotic physics. I would put nuclear physics and vacuum physics in this category. The laser's very high field might not be strong enough. In fact, producing gamma rays is necessary to induce reactions for carrying out nuclear photo physics, for example.

O&P: Looking at the first points, it appears that a major goal of the project is to develop

smaller, more stable laser systems with higher output performance.

G.M.: Yes, but relatively speaking. If I want to produce GeV electrons today, I may use SLAC which makes 50 GeV over three kilometers. If we get that onto the size of a football field then it is a superb achievement. Instead we are envisioning going from a size of 3 km to 50 m. Of course, we know that in about 15 years, high-energy physics will have a problem of going beyond the point they are at now. I think laser acceleration is certainly a promising way of solving that problem. It would be great to get 1 GeV acceleration on a scale of just a few centimeters. And there are many more applications there. We have to work now to be able to reach that within 15 years.

O&P: For most applications the repetition rate of today‘s laser facilities is too small. What‘s your opinion about that?

G.M.: Indeed, we can produce the highest peak power on earth. But we are not yet good in average power. With a terawatt system, we may have 10 pulses per second. We have yet to improve average power. People working at laser fusion have the same problem. They are going to show it in single shots and the have to show a continuous operation. Now we can produce 100 Joules at 10 Hertz, and we are pushing the limits of technology. My next project is to go to the kilowatt or even the megawatt level.

O&P: On average power?

G.M.: Yes. The megawatt will be the challenge. If we want to replace existing high energy accelerator systems with lasers, then we have to show kilojoules at 10 kHz, which means 10 megawatts. And of course, a system like that is orders of magnitudes above what we have. We are working on a new concept based on fibers, called CAN. CAN is the abbreviation of Coherent Amplification Network. We are forming a consortium with the likes of Andreas Tünnermann (Jena) and David Payne (Southampton). We really want to produce lasers with higher average power. But we need to do it really efficiently. We don’t want to produce 10 megawatts with a one percent efficiency. We can do that, but if we want to go into application, this is not feasible anymore. So fiber lasers offer some attractive conditions: they are very efficient, they are diode pumped – again very efficient. The problem is, we have to use a lot of them and we have to couple them coherently. Because we can have only a millijoule in one fiber. The nice thing about fibers is the tremendous work the telecom communities have done there. We are going to send a very nice proposal to Brussels, proposing very efficient lasers. The goal is 30 % to 50 % efficiency. If we can do that, then we can talk about applications. That’s where there‘s a bottle neck.

O&P: What other applications can you imagine?

G.M.: Of course there could be ion therapy, where huge average power is not necessary. If we look at particle acceleration, we could use lasers to transmute elements. Also lasers could be used for nuclear waste processing. Sauerbrey did some very nice demonstrations doing just that. But of course we can not do that with one percent laser efficiency. The same holds for laser fusion as well.

O&P: After an impressive scientific career in Michigan, you have just started one of the biggest laser projects in Europe. What are the next steps?

G.M.: In fact, this is the biggest optics project in the world – in the civilian arena. We really have to build this. But now we need project managers, not scientists. We are talking about 800 million Euros. It will be undertaken in three countries, and it‘s now just about bricks and mortar. The preparatory phase is ending. Now it‘s going to the deliverables consortium. Of course, it has to be close to the community. I will be also active here in the Appollon Project which is producing the prototype laser.

O&P: You spent more than half of your scientific life in the USA. What are the differences in the scientific system in comparison to European research (and education)?

G.M.: Regarding Europe, I can only speak about the French system. In the American system, you have to do three things: research, teaching and services, that is running the department, etc. The important point is the mix of teaching and research and you have to teach everything. I was in optics but I also taught transistors. It is a pain in the neck but can be very nice at the same time. This mélange is very productive. In France we don't have this mix, although this is changing now. In CNRS they do primarily research. In the States, even the senior professors are asked to teach junior courses. They want to see the real teachers doing it, not the grad students. I was the head of a very large center, but I still had to do that. Another point is technology transfer. In the States, there are rarely people on hard money (university budget). Only the professors are paid for teaching. And so all those not teaching are paid by soft money. So you have what we call here precarity. That is very successful for the foundation of startups, because if people do research and stumble on something exciting, they think about starting a business. And making a startup is very natural. All the companies which I started in America, I started with researchers such as Tibor Juhasz, now a multimillionaire. He was not a professor when he started. And starting a company means making money and attaining a better position. And all of them want to break into the industry. I found that fascinating. In America, professors are doing both research and teaching. If you go to the lab all the work is done by grad students. There might be exceptions, for technology at larger institutions. But usually all the work and the presentations are done by the grad students.

O&P: Isn't that a threat to those trained in science, those passionate about pure science?

G.M.: Of course. But we have a lot of universities and people are free to choose. It encourages mobility. You cannot do your post doc where you did your graduate work. Certainly, you can come back after 5 years, but first you have to move.

O&P: Professor Mourou, thank you for this interview.

Notes